

## X-RAY COMPUTED TOMOGRAPHY APPLICATION RESEARCH

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### INTRODUCTION

The value of CT in the medical community has been well documented. Medical computed axial tomography (CAT) scans can provide physicians with valuable information such as the presence, location, size and growth patterns of tumors and abnormalities within the body. This information can be used to judge the severity of the problem, aid in removal through surgery and detect the onset of a problem at an earlier stage than might have been possible otherwise. Outside the medical community CT has been very successful as an NDT modality, such as for the inspection of rocket motors and turbine blades. However its full potential to industry has not yet been realized. This paper will introduce several innovative areas for the application of CT that have proven successful and discuss their potential benefits to the Department of Defense and to industry.

### Computed Tomography

Computed tomography employs a finely collimated X-ray beam, a detector package, and computer algorithms to inspect planes within the object [1]. CT images correspond to faithful reconstructions of cross-sectional profiles. Internal features are not superposed; valuable information on material properties and dimensional characteristics of the object are acquired. Figure 1 illustrates the collection of CT imagery.

### Wright Laboratory/Materials Directorate Computed Tomography Research Facility

CT data included in this paper were acquired using the LAM/DE CT system installed at the Wright Laboratory/Materials Directorate located at Wright-Patterson Air Force Base, OH. ARACOR has held a close working relationship with Wright Laboratory developing both CT systems and providing research expertise through an on-site contract.

LAM/DE is a medium resolution scanner capable of CT, digital radiography, laminography, and dual energy imaging. This system allows inspection of components with physical dimensions of 600 mm (2 ft.) in diameter, 400 mm (16 in.) in height and up to 250 lbs (115 kg). The radiation source is a Seifert 420 keV X-ray tube. Typical CT scan times

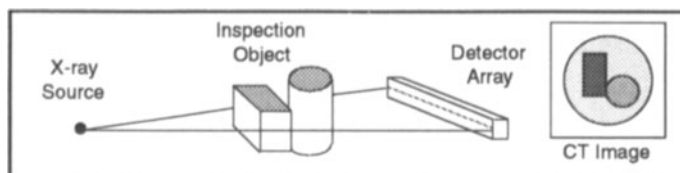


Figure 1. Illustration of computed tomography.

for the system range from 15 to 30 minutes with a typical resolution of about 1 mm (40 mils). The LAM/DE scanner was developed under funding from the Air Force Wright Laboratory and has been operational since 1987.

## COMPUTED TOMOGRAPHY APPLICATIONS

### Dimensional Measurement

Dimensional characterization of intricate components with detailed internal features is both costly and time consuming by traditional methods. Customary metrology tools include coordinate measuring machines (CMM) and laser scanning systems. CMM records surface profiles of a part through the intimate contact of a probe moving along the surface. Laser scanning provides a topographical map of the surface of an object by using a non-contact laser beam. To acquire information on internal features, CMM and laser scanning require destructive sectioning to expose internal details. A measurement technique based on CT technology would allow geometric interrogation and characterization of inaccessible features without destroying the part.

A study was conducted at the Computed Tomography Research Facility to determine the feasibility of using CT for dimensional inspections [2]. Sets of independent measurements were acquired from two different castings to determine not only the wall measurements but the confidence of those measurements. Following the CT measurement of the two castings, the manufacturer measured the thin wall regions using conventional methods. The castings were sectioned open and the thin wall region was incrementally milled and measured. The standard deviation for each set of CT measurements was about 0.001 inches (1 mil). Thus, wall measurements from CT data can be determined with a three-sigma confidence of about  $\pm 0.003$  inches. For both castings, the cut-up evaluation measurements were within the three-sigma confidence interval.

Using CT for dimensional measurement has several advantages over traditional methods of dimensional characterization. CT is nondestructive; internal features can be measured without losing the asset. CT dimensional characterization can be performed without part-dependent programming as is common with coordinate measuring machine methods. The measurement procedure can easily be applied to a wide variety of objects with various geometries and material compositions. CT imagery can be collected in times ranging from a few minutes to a few hours. A tremendous cost savings over traditional methods is realized with CT analysis; parts are preserved, programming time is not required, and CT analysis of a complex part can be done in a matter of several hours.

**Reverse Engineering.** Another area of CT application related to dimensional measurement is reverse engineering. Reverse engineering is an important technology to the Department of Defense and in the manufacturing industry. Often in the manufacturing of spare or replacement parts, CAD descriptions or even original hard copy drawings do not exist. In other cases, drawings may be inaccurate due to manufacturing process changes

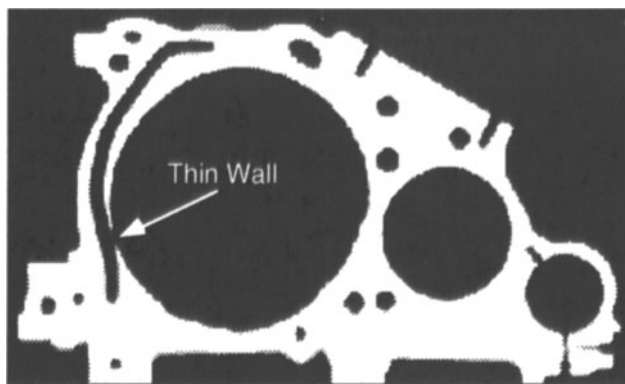


Figure 2: CT image showing thin wall region.

that were never updated on the drawing or CAD file. With CNC machining or rapid prototyping applications, a CAD file is required and must be generated from hard copy drawings if the CAD description does not yet exist.

Given that thin walls can be accurately measured through CT analysis, it is a simple extrapolation to acquire precision contour data through the entire image or a set of images. CAD representations of original parts can then be generated from the contour data [3]. A program sponsored by the Defense Logistics Agency (Attn: DLA-AQPOT, Cameron Station, Alexandria, VA 22304-6100) examined this process. Figure 3 shows a photograph of an aluminum boat propeller. A contiguous set of 170 CT images was acquired from the propeller. A point cloud description of the propeller was extracted from the CT data set. Surfacr™ from Imageware was used to create the surface model shown in Figure 4. From the CAD surface model, a solid model (for CAD design modifications) or an STL file (for rapid prototyping) can easily be generated. CT can provide a quick, cost effective method of creating CAD representations of existing parts or of comparing an existing component with its engineering documentation.

### Process Development

Process development has long been an arduous trial-and-error task of altering one or two process parameters and testing the part to evaluate the effects of the process changes. This procedure is costly in both time and money, particularly for modern materials that have complex processing cycles. There are four notable areas where CT can provide useful process development information and be cost effective [4]. These areas are 1) substitution for destructive analysis, 2) supplying data for effect of defect studies, 3) pedigree evaluation, and 4) model verification. These uses of CT can reduce process development time and cost as well as provide more confidence in the final processed part.

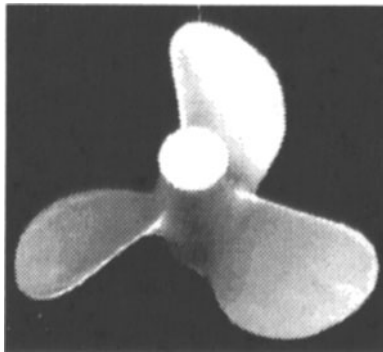


Figure 3. Photograph of propeller.

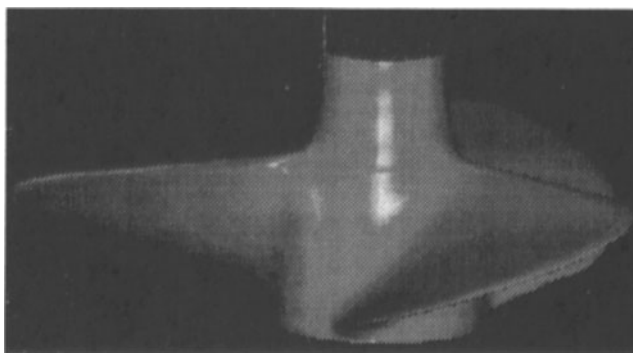


Figure 4. Surface model of propeller created from CT data.

Destructive Analysis. Process development groups often expend substantial resources performing destructive evaluation of materials and components to understand and characterize the internal makeup of parts. For example, foundries will often cut-up several castings to inspect for material and dimensional anomalies. Destructive evaluation efforts entail several disadvantages which primarily include the extensive cost associated with losing many components to cut-ups, the time involved in labor intensive characterization of the cut-up sections, and the inability to gather comprehensive data critical for expedient assessment of casting process parameters. CT can act as a substitute for a number of destructive analysis techniques currently used and provides added capabilities thus far unattainable by traditional methods.

Effect of Defect Studies. The term “defect” is often a very difficult one to define. For example a crack, termed as a defect, may not be detrimental to the part. This concept is very important in composite materials since traditionally defined damage such as cracks may actually enhance the performance of some composites. Cracks in certain composites can relieve stress concentrations thus improving part performance. As materials become increasingly complex, the term “defect” needs to be used very carefully. CT can assist in determining the impact of a particular defect on part performance. Features identified prior to material testing can be correlated with test results. This allows process development efforts to focus on those defects that truly degrade part performance.

Pedigree Evaluation. Many modern materials undergo a number of complex processing steps. Some ceramic-matrix composite (CMC) materials undergo repeated lay-up, consolidation, curing, and post-curing cycles before the process is complete. CT can be used to detect incipient flaws in the early stages of process development. When detected early, these precursors to material degradation can be corrected or, at worst, unnecessary processing of flawed material can be avoided. If parts are only inspected at the end of all processing or at limited stages, then underlying causes leading to defects cannot be easily ascertained. Pedigree evaluation provides a method of tracking the evolution of a defect while optimizing a process. CT data used in this manner can significantly expedite new development efforts.

As an example, CT was used for pedigree evaluation of CMC components being developed for use in high-performance turbine engines. Chemical vapor deposition (CVD) is a technique being investigated for fabrication of CMC components. CVD takes a ceramic fiber preform and forces a hot gas into the structure which deposits ceramic material on the fibers. Several processing runs are required for each component. A goal of CVD processing is to produce a component free of excessive porosity while minimizing the number of required CVD runs. A potential problem with CVD processing is that the chemical vapors preferentially deposit ceramic material on the outer layer and near surface areas of the preform. The external surfaces can densify to the point that interior areas of the part are no longer subjected to the vapors. This can result in significant porosity (or lower mean density) at the center of the part as well as wasted processing time. CT can track internal density gradients and surface densification after each processing run. This characterizes the process in such a way that the optimum number of CVD runs is identified. Eliminating CVD runs or reducing the time of each run can translate into significant cost savings.

The CT images in Figure 6 show CT imagery from a 200 mm diameter CMC disk at two stages of CVD processing. The image on the left shows the disk after one CVD run and covers a density range of approximately 1.0 g/cc to 1.9 g/cc. The image on the right shows the disk after four CVD runs and covers the density range of approximately 1.4 g/cc to 2.0 g/cc. Density values along a line through the disk are graphed below each image. In both disks, the density is lowest midway between the outside surface and the inner hole. However, after four CVD runs, the variation is less dramatic and the disk is becoming more uniformly dense.

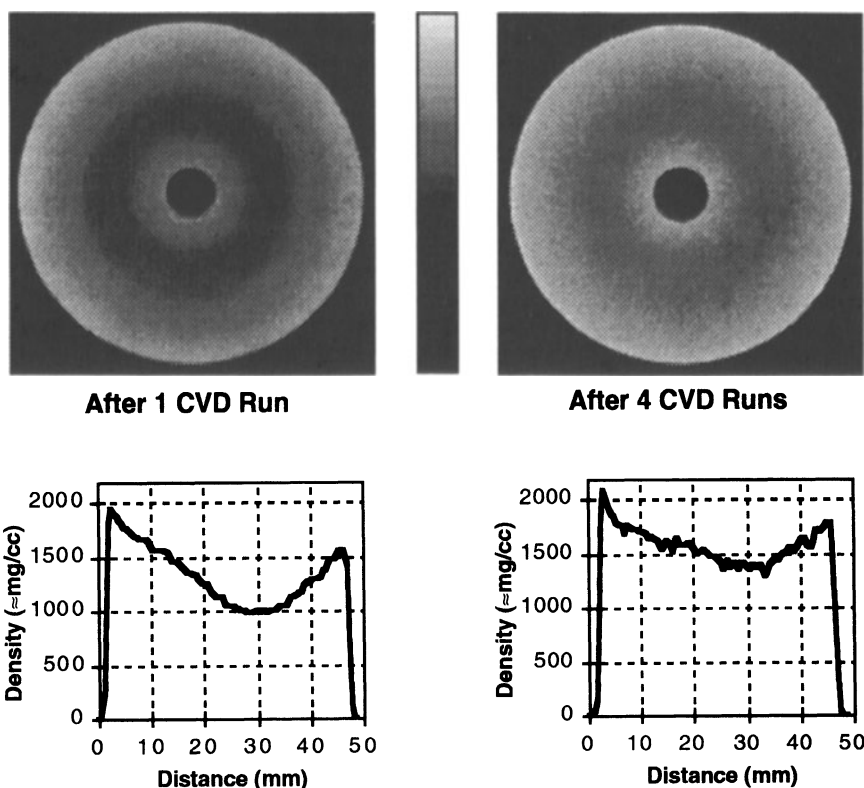


Figure 6: Pedigree evaluation of chemical vapor deposition (CVD) process.

**Model Verification.** Another area of process development where CT can make an impact is in the verification of processing and structural models [5]. Models generally require information regarding the internal structure of the object to be analyzed. For example, a simple mechanical analysis of a composite material would require as input the volume fraction of the fibers relative to the matrix. A more complex model may require data on the spatial distribution of the fibers while an even more complex model may need the location of porosity or defects and other variations in density within the matrix. A typical approach to obtaining this data would be to make assumptions for a given part based on destructive analysis of similar components. CT can provide a significant advantage over this approach in that the internal makeup of the actual test object can be determined and used as input to the model. Predictions from the model can then be compared with test results and destructive analysis.

## CONCLUSIONS

Research was conducted on a variety of applications for many different customers. Some key themes emerged from the research in the areas of how CT can be used effectively. CT can be a powerful tool for process development by using it as a substitute for destructive analysis, to perform effect of defect studies, and to follow parts through successive stages of processing. CT is also effective as a tool for design verification, model verification, failure analysis, and quality assurance. Application areas studied include advanced composites (metal-, ceramic-, and polymer-matrix composites), aeropropulsion structures, flight vehicle structures, metal castings, advanced ceramics, electronic components, rocket propellant, and space vehicle components. Many of these application studies resulted in a better understanding of how CT can be best utilized. The studies also

resulted in new tools or capabilities that make CT inspection more efficient and useful. Some of these tools include the development of methodologies for the accurate dimensional measurement of internal passages in metal castings, reverse engineering capabilities to turn CT image data into CAD representations of components, customized image analysis tools for extraction of key information from the images such as fiber positions in metal-matrix composites, and 3-D image rendering from a series of contiguous CT slices.

The key conclusion from the research is the broad range of uses for X-ray CT. CT can be much more than a quality assurance tool to inspect materials or components at the end of the manufacturing cycle. In many cases, CT is most effective when used up-front during the development of new material systems, new material processes, or new manufacturing procedures. The value of this approach is apparent from this research as CT can provide quick and accurate information on the internal features of materials and components.

## ACKNOWLEDGMENTS

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